ROBUST DETERMINATION OF ROCK ANISOTROPY IN THE LABORATORY USING LASER ULTRASONICS

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Session Title: MR43A - Physical Properties of Earth Materials (PPEM): The Long and the Short of It | Oral

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AGU FALL MEETING

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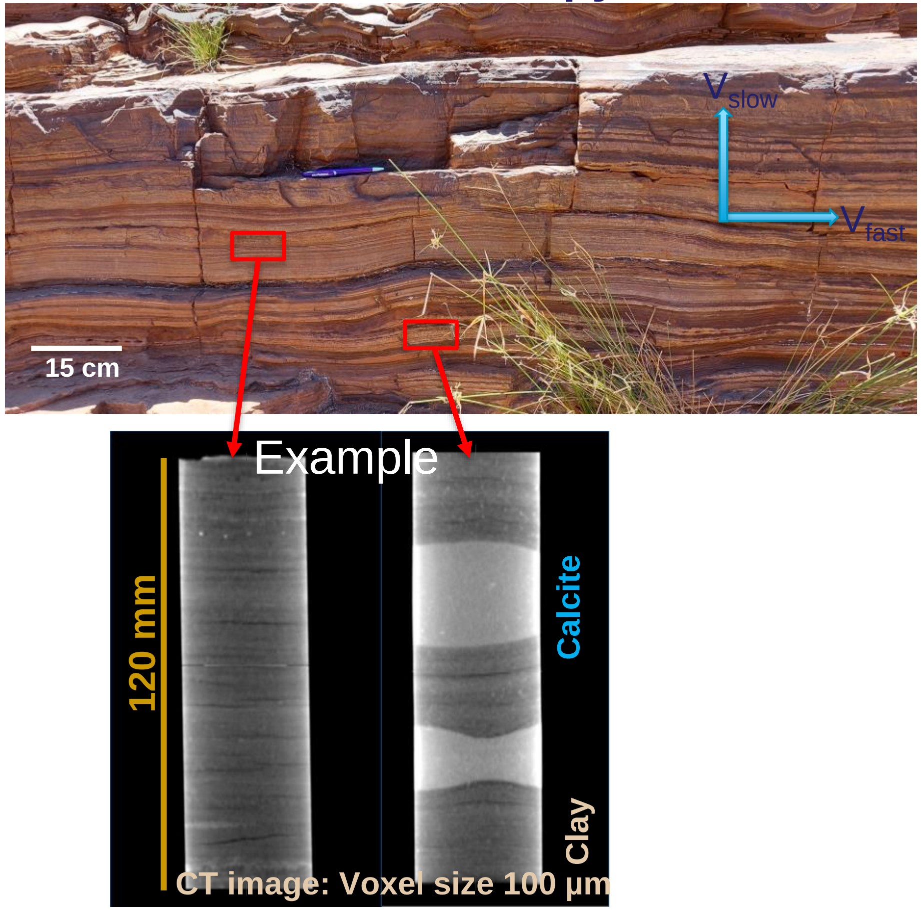
AGENDA

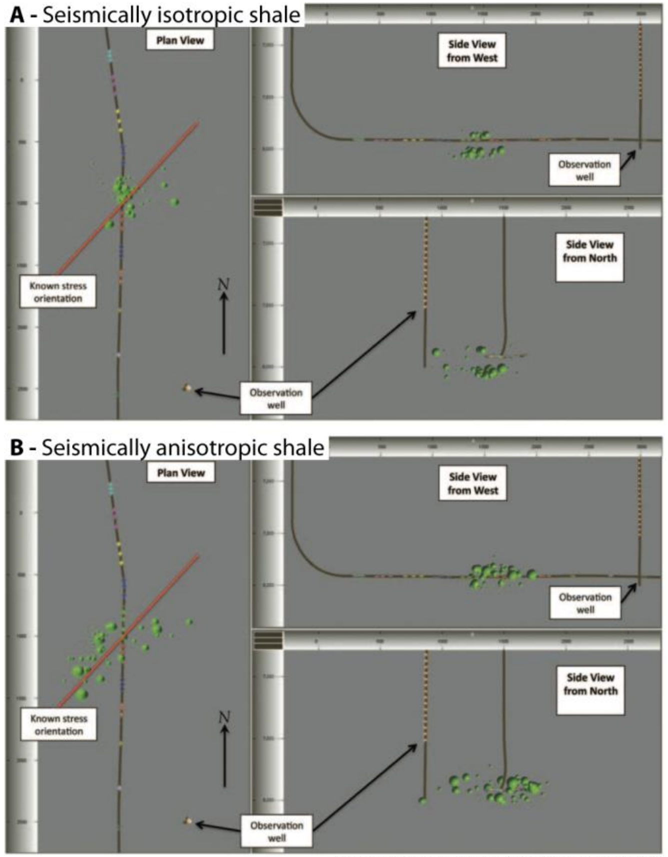
- Background – shale anisotropy
- Rationale – laboratory technique
- Laser Ultrasonic Survey (LUS) & sample characterization
- LUS waveform Inversion (Thomsen's anisotropy parameters & Symmetry axis orientation)
- Advantages & limitations of LUS
- Conclusions

BACKGROUND – SHALE ANISOTROPY

Rock anisotropy

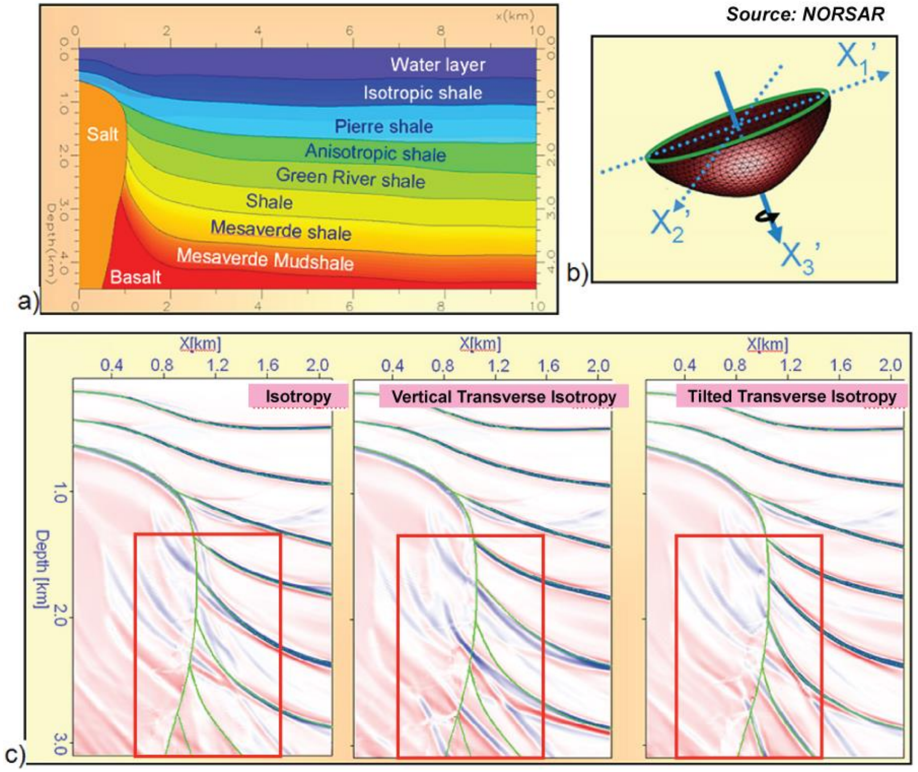


Subsurface stress distribution & hydraulic fracturing – shale



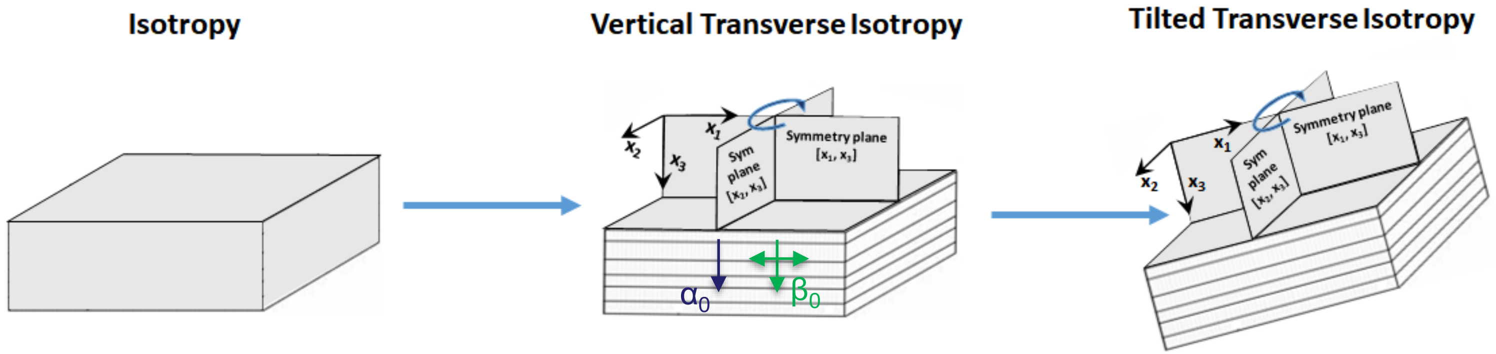
Bakken shale, North Dakota, from Van Dok et al. (2011)

Subsurface seismic imaging



RATIONALE – DESCRIBING TRANSVERSE ISOTROPY (TI)

Five independent parameters α_0, β_0 , ε, γ , δ (Thomsen, 1986) to describe TI media (in a known symmetry frame, azimuth angle *p* and dip angle *q* of the symmetry axis):



He et al., 2013

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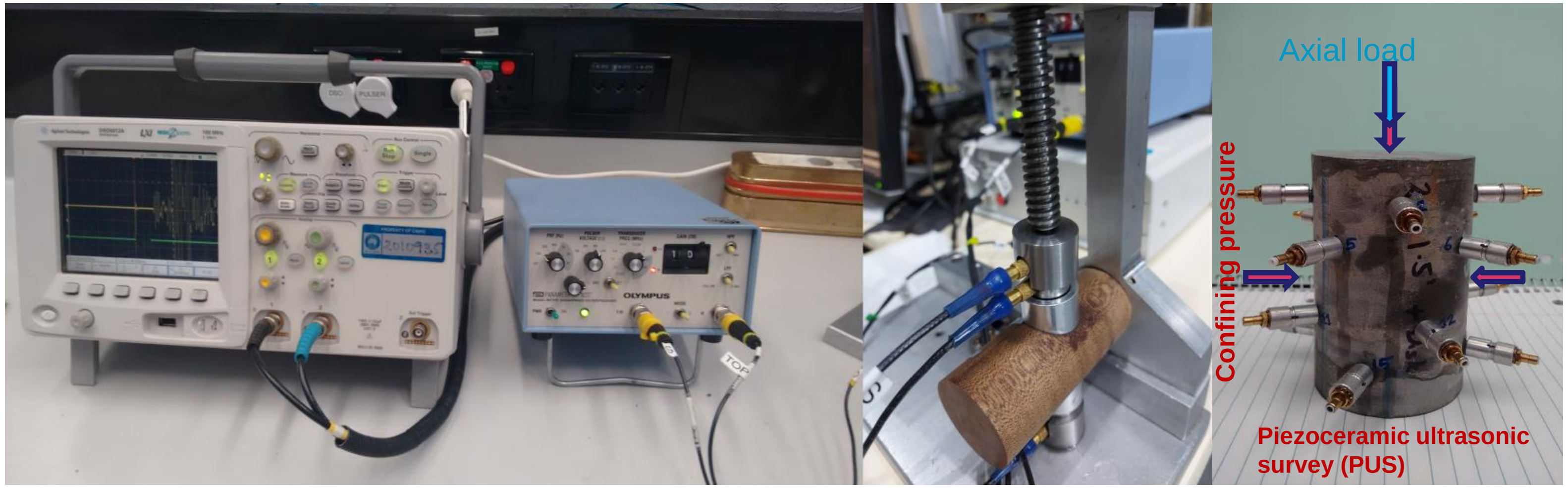
RATIONALE – PIEZOCERAMIC ULTRASONIC SURVEY (PUS)

- Which conventional technique is used to define Thomsen's anisotropy parameters?
- <u>Thomsen's anisotropy parameters</u> (α_0, ε, δ) and orientation of symmetry axis from inversion of P-wave velocities with PUS
- Challenges of PUS setup?



Oscilloscope Pulser Transducers

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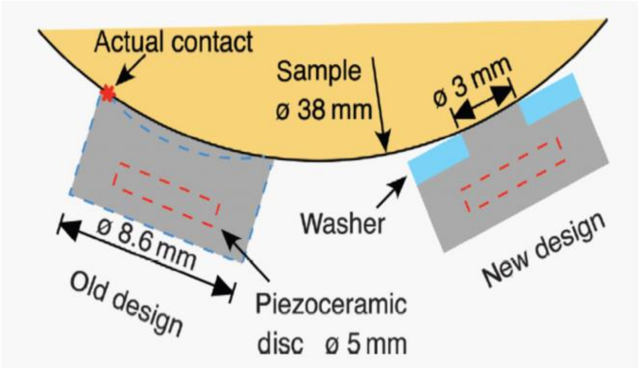
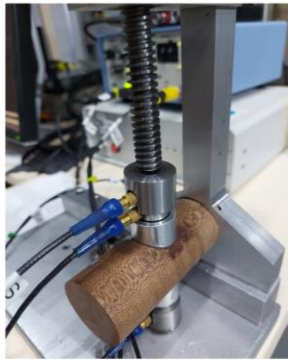
CHALLENGES OF PUS

- Phase or group velocity measurement?
- Coupling ?
- Sampling density?
- Identification of fast and slow P-wave direction in TI media?

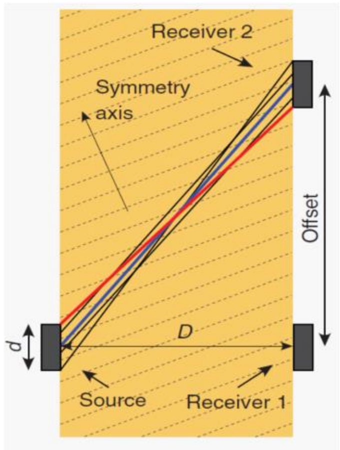
Transducer size



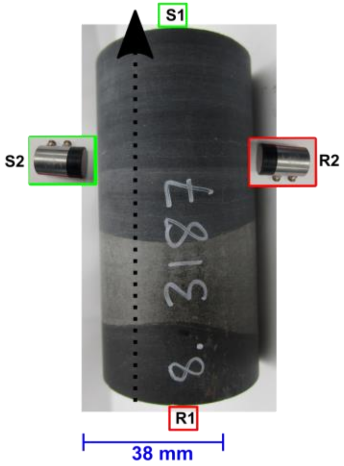
Coupling



Propogation path

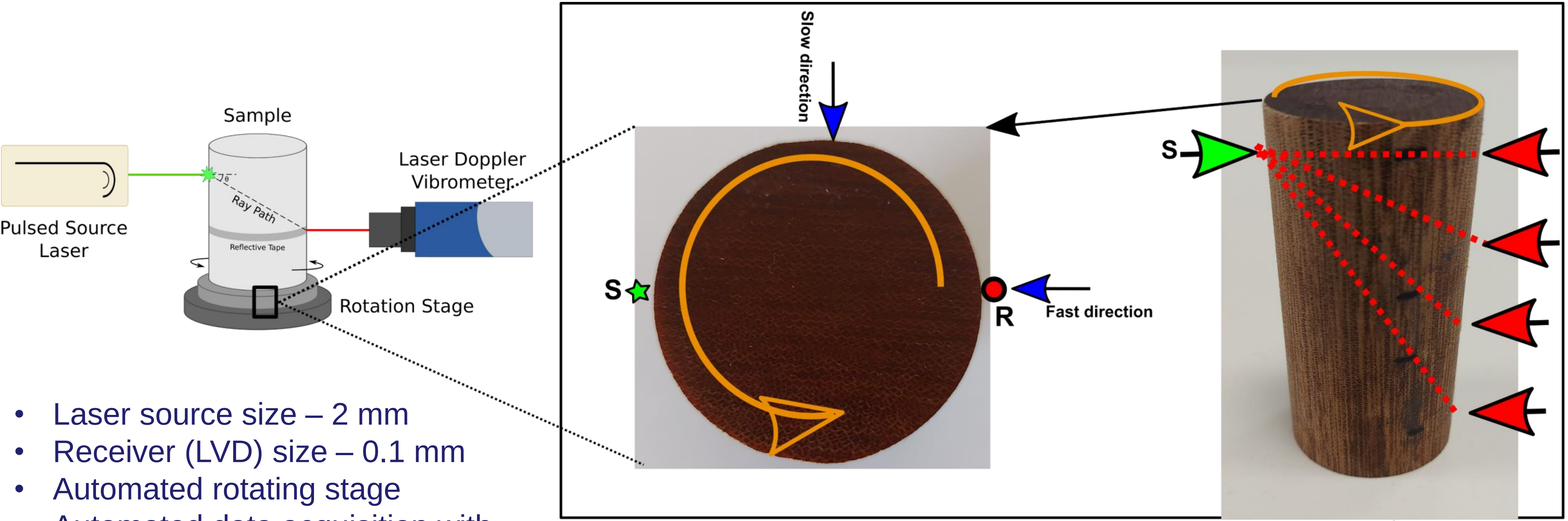


known axis of symmetry



(Kovalyshen et al., 2020 ; Kovalyshen et al., 2017)

LUS EXPERIMENT PROTOCOL



- Laser source size – 2 mm
- Receiver (LVD) size – 0.1 mm
- Automated rotating stage
- Automated data acquisition with PLACE
- Double LVD configuration

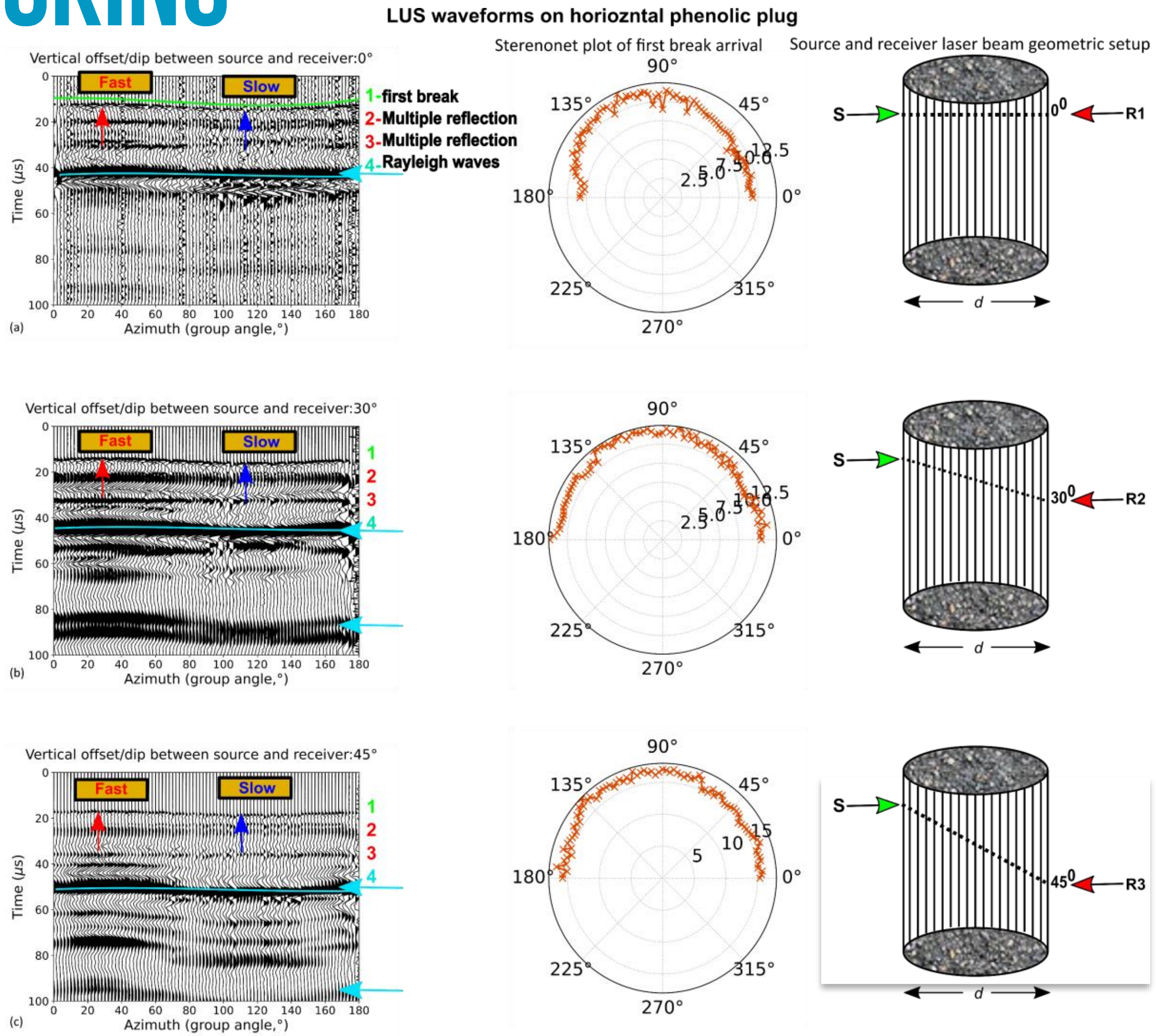
Simpson et al., 2019; Simpson, 2019; PAL, The University of Auckland

SAMPLE CHARACTERIZATION

- Length to diameter ratio (l/d)- 2:1
- Heterogenous vertical shale Th8 sample – Goldwyer shale formation
- Porosity and bulk density of Th8 are 8.6% and 2.6 g/cc

LUS WAVEFORM & FIRST BREAK PICKING

- AIC algorithm to pick first break arrival
- Repeated reflections (Multiple) of the body waves
- Fast and slow P-wave direction – from waveform and polar diagram
- Surface Rayleigh wave



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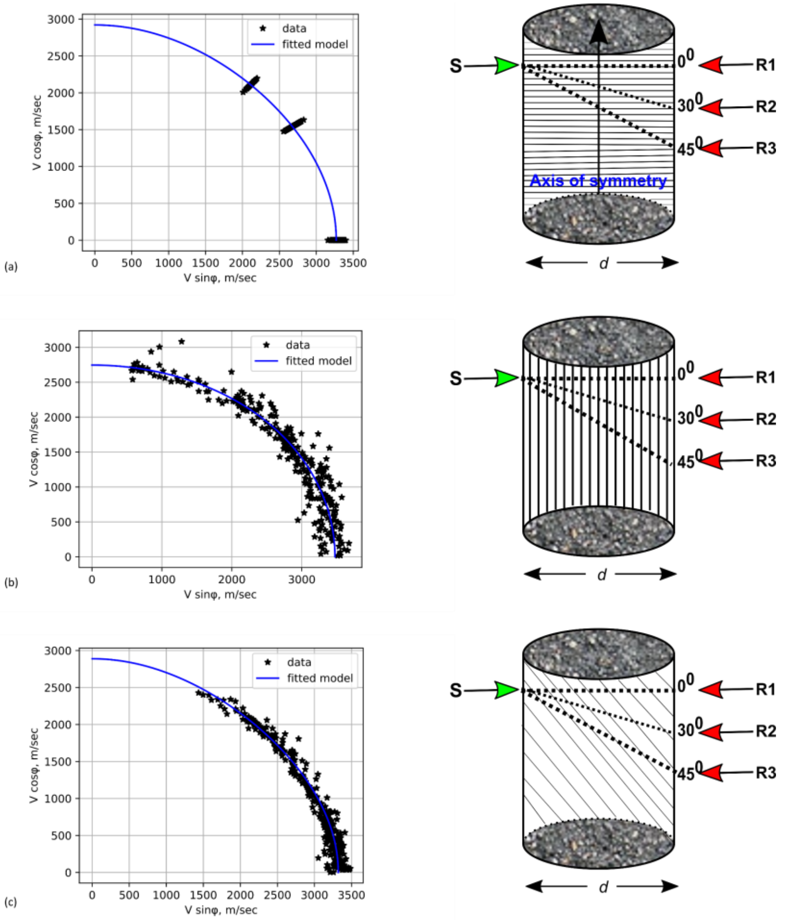
INVERSION & ASSUMPTIONS



$$F(\alpha_0, \varepsilon, \delta, p, q) = \sum_i \left[1 - V^i_{model}(\alpha_0, \varepsilon, \delta, p, q)/V^i_{measured}\right]^2$$

- TI media & β_0/α_0 ratio from PUS
- Inversion algorithm (least-square regression) from Kovalyshen et al., 2020
- Output parameters are p, q, α_0, ε, δ

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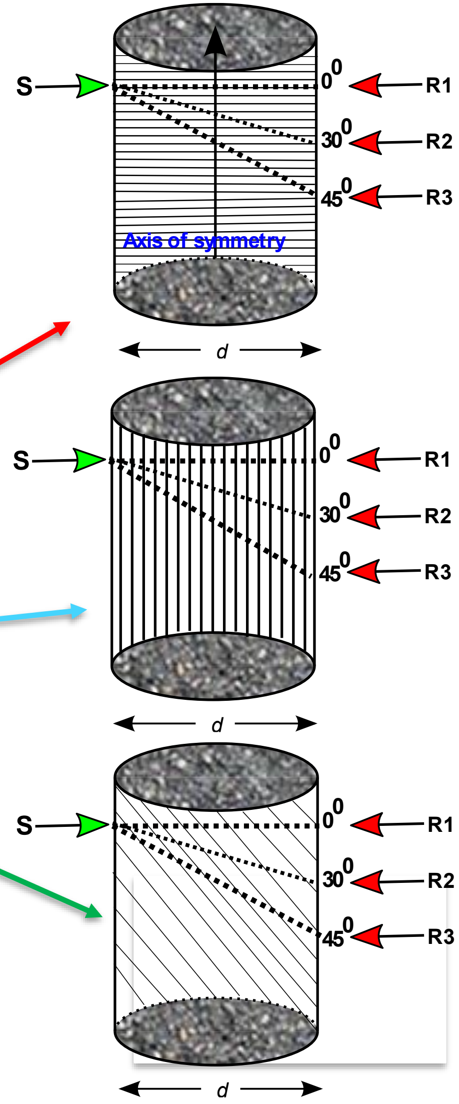
RESULTS

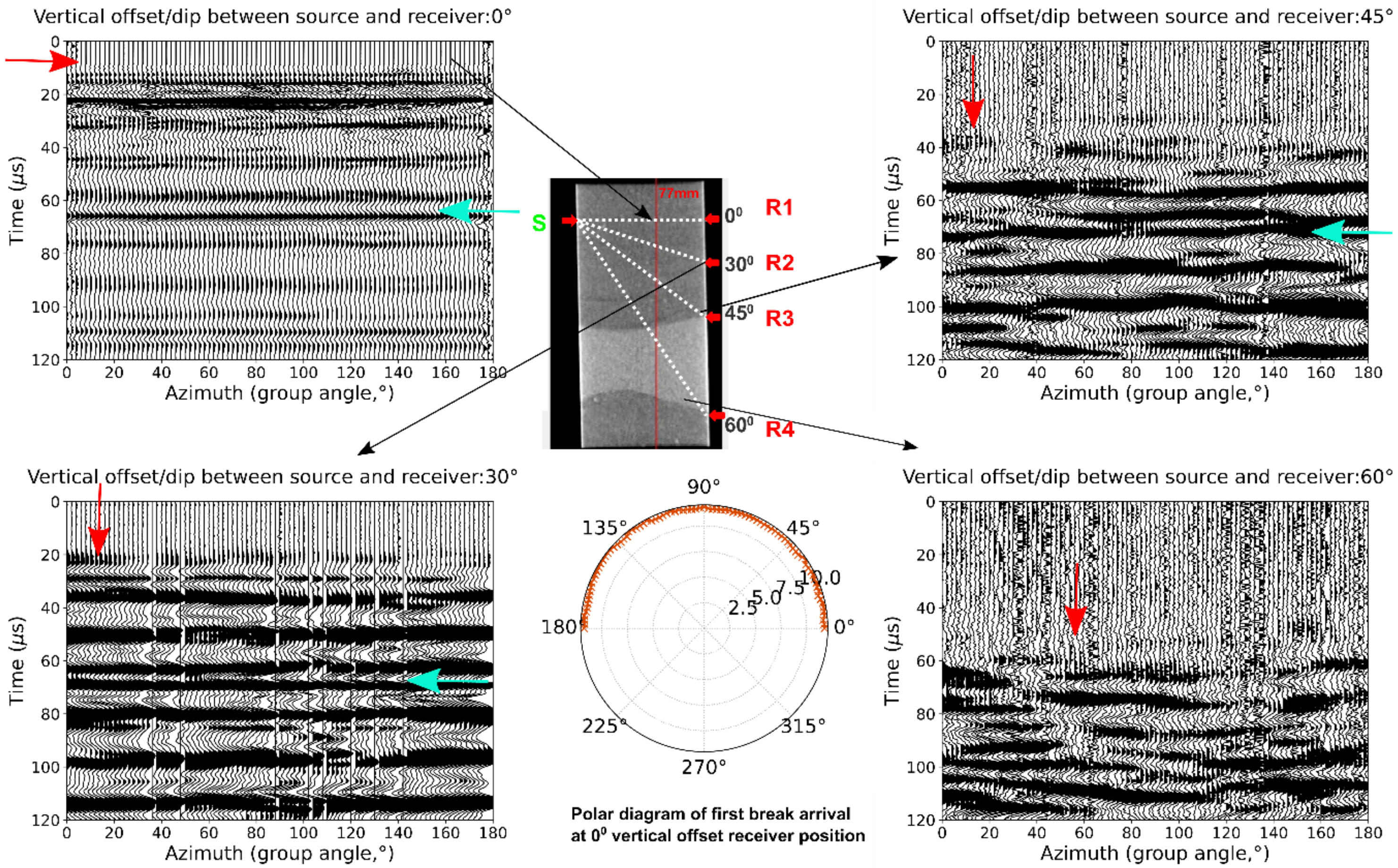
	Sample orientation	p (º)	q (º)	α_0 (km/s)	ε (-)	δ (-)
Literature data	Vertical	0	0	2.8	0.22	0.26
Inversion results	Vertical*	0*	0*	2.92	0.13	n/a*
Literature data	Horizontal	90	90	2.8	0.22	0.26
Inversion results	Horizontal	109	78	2.75	0.30	0.35
Literature data	Inclined (45^0)	45	45	2.8	0.22	0.26
Inversion results	Inclined (45^0)	44	44	2.88	0.16	0.04

** For the vertical sample, no inversion is possible due to the limited number of independent ray paths*



LUS APPLICATION ON VERTICAL SHALE SAMPLE

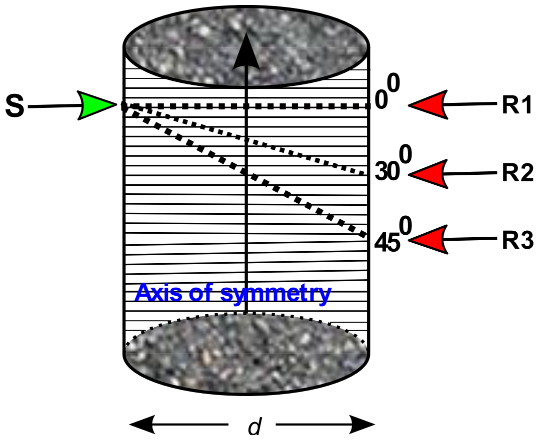
- First break attenuated at 45^0 and 60^0 LVD receiver location
- Polar diagram confirms TI media assumption
- Poor S/N ratio for far offset receiver

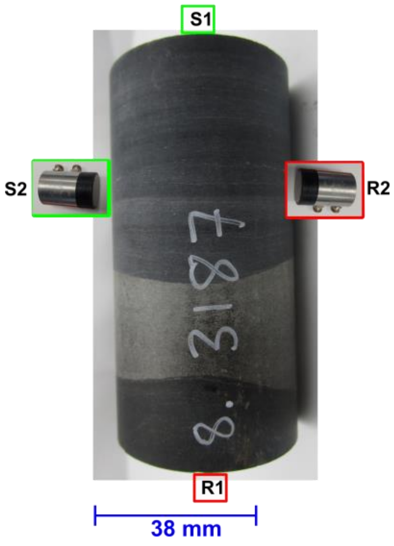


LUS VS PUS – INVERTED PARAMETERS

	Sample orientation	p (º)	q (º)	α_0 (km/s)	ε (-)	δ (-)
PUS measurements	Vertical*	0*	0*	1.73	1.58	n/a*
LUS inversion results	Vertical*	0*	0*	1.59 ± 0.11	1.57 ± 0.29	n/a*

**The orientation of symmetry axis assumed to be vertical based on visual inspection of the top part of the shale sample (homogeneous and layered)*





ADVANTAGES/LIMITATIONS: LUS VS PUS

Criteria	PUS	LUS
Transducer size	Finite size	Point source-receiver
Velocity type	Group/phase ambiguity	Group velocity
Data recording	Sparsely sampled	Densely sampled in space and time
Signal quality	Stronger P-wave arrival	Weaker P-wave arrival
Symmetry orientation and elastic anisotropy	Bedding parallel/inclined plugs	Bedding parallel

CONCLUSIONS

- LUS technique removes ambiguity of coupling, transducers size and phase/group velocity
- Dense LUS data on a single plug parallel to the visible bedding plane allows accurate estimation of symmetry axis orientation (p, q) and Thomsen's anisotropy parameters (α_0, ε, δ)
- Beyond first break arrival, remaining waveforms can provide insight of rock heterogeneity
- Scope to improve S/N ratio with higher source energy and acquisition with single source-receiver pair

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MORE AGU TALKS ON LUS APPLICATION

- MR35B-15 - The Effects of Pressure, Temperature, and Microstructure on the Nonlinear Softening and Recovery of Fault Rocks - Jonathan Simpson*, Kasper van Wijk and Ludmila Adam
- U53A-07 - Probing the Nonlinear Behavior of Rocks to Understand Dynamic Triggering of Earthquakes and Volcanoes (Invited) - Jonathan Simpson*, Kasper van Wijk and Ludmila Adam

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CSIRO

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THANK YOU

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